Proceedings of the Twenty-second (2012) International Offshore and Polar Engineering Conference
Rhodes, Greece, June 17–22, 2012

ISBN 978-1-880653-94-4 (Set); ISSN 1098-6189 (Set)

www.isope.org

Effect of Coupling Wave and Flow Dynamics on Hurricane Surge and Inundation

Jayaram Veeramony, Andrew Condon and David Hebert
Naval Research Lab
Stennis Space Center, Mississippi, USA

ABSTRACT

Inundation that results from tropical storms and hurricanes significantly impact coastal communities. The ability to predict the extent of surge and inundation is essential for evacuation orders, disaster response preparation, and resource planning. In this study we validate the DELFT3D modeling suite comprised of FLOW and WAVE modules to model inundation caused by Hurricane Ike (2008) using reanalyzed data. Model results are compared to the data collected by the SURA coastal inundation testbed. Comparing the effects of coupling waves show that there water levels when coupling waves is substantially greater on the eastern side of the storm where the wind is landward, than on the western side.

KEY WORDS: Storm Surge; Inundation, Coupled Modelling.

INTRODUCTION

Coastal communities, especially in the mid latitude regions, are significantly impacted hurricanes – both by the wind fields as well as by the accompanying surge. Forecasting the extent of the inundation is critical for local emergency operations in order to issue evacuation orders and to muster critical supplies for post-storm recovery. To estimate the inundation extent, a highly accurate, high resolution, surge and inundation modeling system is needed. Currently operational modeling relies on one of two approaches to determine the intensity of storm surge: modeled surge values from historical storms are combined with information on historical storm frequencies to estimate local surge hazards; and in the other, ensemble model runs are used to determine surge values from a set of parameterized storms [Irish et al., 2011]. Both these approaches rely on storms of a defined strength having similar characteristics. In the instance of storms with outlier tendencies, such as Hurricane Ike, which had wind velocities of a Category 2 storm, but a central pressure of a Category 3/4 storm and a larger than normal extent of hurricane force wind speeds, these methods become unreliable.

Storm surge is primarily generated by the extreme winds from a low-pressure atmospheric system [Dean and Dalrymple, 2002]. The magnitude of the surge increases with the wind speed and size of the storm for a given coastal region [Irish et al., 2008]. Many secondary factors also influence the magnitude of the storm surge including the Coriolis effect in the form of coastal upwelling / downwelling and forerunners [Dean and Dalrymple, 2002; Kennedy et al., 2011], wave effects [Dietrich et al. 2008; Sheng et al. 2010] and the barometric pressure of the storm [Jelesnianski et al. 1992]. While these factors may be secondary to the winds in generating surge, they can be significant under certain storm conditions and coastal environments. In addition to the storm surge, the astronomical tide level combines with the storm surge to create the storm tide. The extent of coastal inundation - flooding of inland surface that is not normally submerged, is determined by the height of the storm tide and elevation of the land surface.

In order to accurately predict coastal inundation, storm surge generating forces need to be accurately represented. Wind magnitude, direction, and distribution as well as the pressure distribution of the storm needs to be represented correctly. Large scale effects that can contribute to Coriolis effects along the coastline must also be included. Waves in both the nearshore and offshore are needed so that wave setup effects along the coast are correct. The coastal hydrodynamics must be correct for both storm surge and astronomical tide predictions as well. In addition, the bathymetry and topography data in the area of interest must be adequately represented so that reasonable estimates of the inundation extent can take place. These many components need to be combined in a storm surge modeling system to predict coastal storm surge and inundation. In this study, we present the results from a study using the Delft3D modeling system, which is a predictive model, applied to Hurricane Ike which impacted a number of areas along "hurricane alley", including but not limited to Turks and Caicos Islands, Hispaniola, Cuba and the United States. We concentrate especially on the northern Gulf of Mexico coast due to the availability of a large number of observations from this region.

Hurricane Ike made landfall in the US as a strong category 2 storm near Galveston, TX around 0700 UTC, Sep 13, 2008. The storm surge from Ike reached the southwest coast of Louisiana well ahead of landfall [Kennedy et al., 2011], and over the course of the next couple of days caused substantial flooding along the Louisiana-Texas coastline. After Hurricane Katrina (2005), a number of gauges have been deployed in this region, yielding numerous measurements of water levels and wave conditions. As a result, for Hurricane Ike, water level data is available from 158 stations from the U.S. Army Corps of Engineers (USACE),

20121207082 20121212070
20121212082

the U.S. Geological Survey (USGS), the National Oceanic and Atmospheric Administration (NOAA), and the Coastwide Reference Monitoring System (CRMS) and wave data from 18 NDBC moored buoys. These data have been compiled as part of the super-regional testbed for improving forecasts of environmental processes for the U.S. Atlantic and Gulf of Mexico coasts led by Southern Universities Research Association (SURA).

STORM SURGE MODEL

Model Description

The model of choice for this study of hurricane storm surge is Delft3D [Stelling, 1997; Lesser et al., 2004]. The Delft3D system consists of a number of components, the main one being Delft3D-FLOW. Delf3D-FLOW models the hydrodynamic flow under the shallow water assumption. It includes a large number of processes, including those relevant for modeling flow caused by hurricanes such as wind, wave forces, tidal forces, and atmospheric pressure changes. Furthermore, although the FLOW module can be run in 3D mode, for modeling the storm surge in this study we choose to run the model in horizontal 2D mode.

Wave effects are included in the Delft3D system by running a separate module called Delft3D-WAVE and is based on the SWAN model [Holthuijsen et al., 1993] In the Delft3D system, communication between the WAVE and FLOW modules are accomplished using files. The WAVE module outputs the wave spectra information and the wave forces and in turn receives from the FLOW module the surface currents, wind information, water level, and bathymetry. Other modules such as morphology are available, but not used in this particular study. The user has the choice of determining the level of coupling between the two modules. They can be one-way coupled, where the information from WAVE is used in FLOW, partially/fully coupled where one or more of currents, winds, water level and bathymetry changes are passed from FLOW to WAVE. The frequency of communication is also adjustable.

Both FLOW and WAVE modules can be run in nested mode, allowing the use of coarser resolution grids in the overall region and fine resolution grids closer to the shore. Multiple nests can be used to get finer resolutions in areas where higher accuracy is required.

Model Results

For Hurricane Ike studies shown here, the model domain is the Gulf of Mexico (Figure 1). The FLOW module had two nests. The large domain that included the entire Gulf of Mexico was tested with three different resolutions; the first had a 0.1 deg resolution, the next with 0.05 deg resolution and the final with 0.025 deg resolution. The region around Galveston, TX had a resolution of 1/5th of the large domain (shown as the red box in Fig. 1.). The resolution of the wave domain was 0.1 deg. The resolution of the outer domain for the FLOW module had a significant effect on the water level predictions in the region (Fig. 2). Increasing the resolution of the large domain to 0.05 deg results in a diurnal tide in the Gulf. This corresponds to the observations, whereas the low-resolution grid amplifies the semi-diurnal tide. Increasing the resolution further to 0.025 deg did not significantly improve the results. Increasing the resolution of the WAVE module also did not significantly improve the wave statistics. The modules are executed in fully coupled mode with information exchanged every hour. More frequent exchange of information does not change the results. Less frequent exchange of information was not tested.

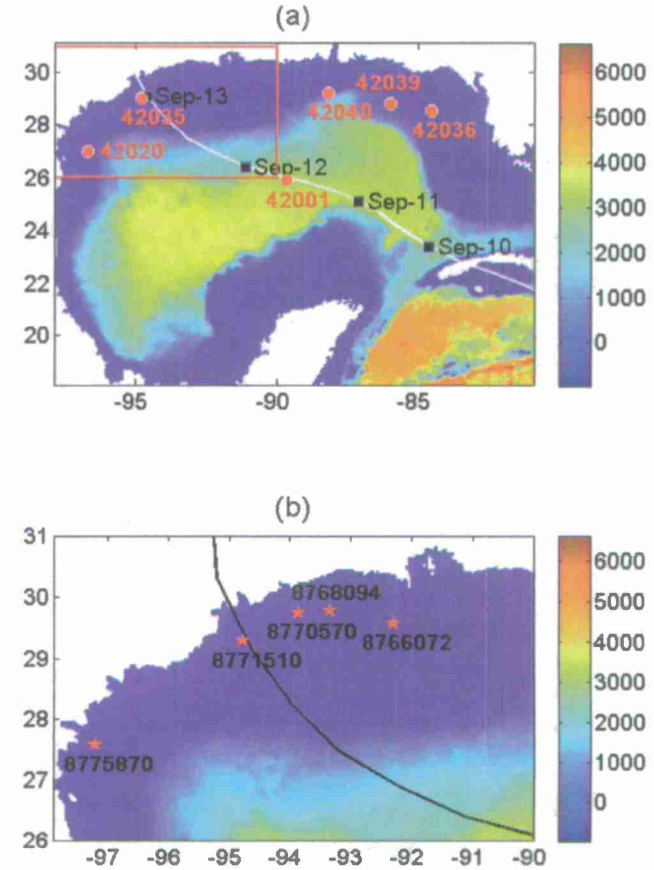

Fig. 1: (a) Model domain showing the bathymetry and topography along the south Texas and Louisiana coast (in meters) and the track (white line) of Hurricane Ike. The timeline shown on the track is in UTC at 0600 hrs. The symbols show the locations of the NDBC stations at which model-data comparisons are made. (b) shows the region bounded by the red line in panel (a) along with the water level stations at which model-data comparisons are made.

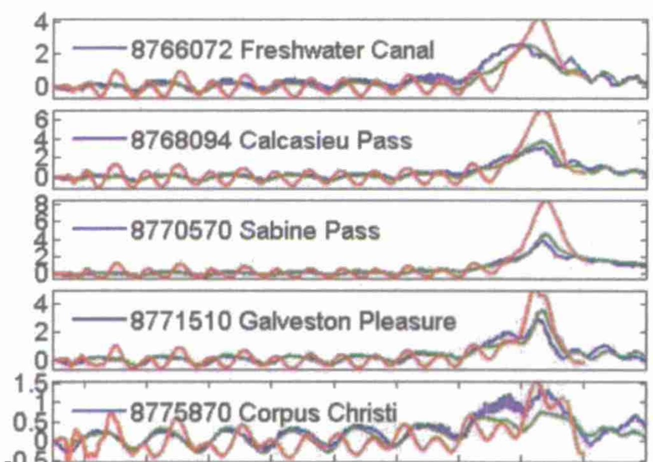

Fig. 2: Comparison of water level (in meters) computed using the coarse resolution grid (red) to that from the fine resolution grid (green). The observations are shown in blue. X-axis shows the days in the month of September.

Hurricane Ike was a Category 2 storm at landfall (175 km/h) on the Saffir-Simpson scale; however had a central pressure of 950 hPa which is typically associated with a strong Category 3 or Category 4 hurricane. Also, hurricane force winds (>118 km/h) extended 200 km from the center of the storm and tropical storm force winds (>63 km/h) extended 400 km from the center of the storm, making Ike one of the largest observed hurricanes in the Atlantic in the past 30 years.

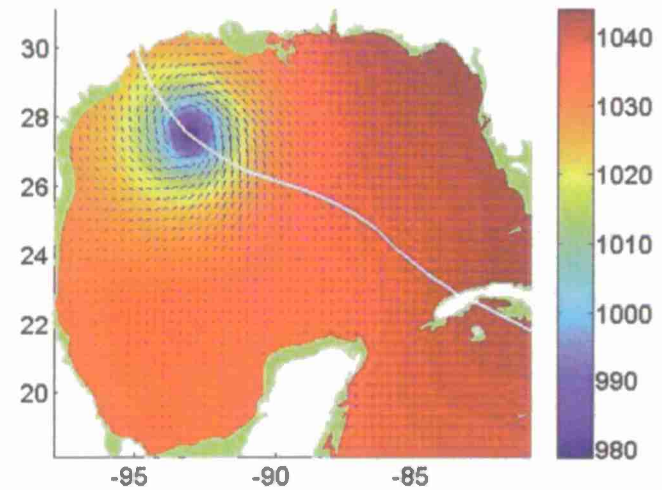

Fig. 3: Reconstructed pressure drop (in hPa) and wind field associated with Hurricane Ike on Sep 12, 1815 UTC.

The hurricane wind fields for the results shown here were obtained from a H*Wind post storm reconstruction which combined available wind information from model and data [Cox et al., 1995; Powell et al., 1998] to derive a consistent U_{10} velocity field. The wind field had a resolution of 0.02 deg in space and 15 mins in time. The wind field at a representative time along with the pressure-drop is shown in Fig. 3. The reconstructed pressure drop does not seem to have the same value. The increase in water level for every hectopascal drop in central pressure is about 0.01 m, which would imply that the results will be underestimating the actual surge by about 0.3 m. compared to about 5-7 m surge recorded at landfall. The surface wind stress is computed using a drag coefficient dependent on wind speed, with corrections for strong winds adapted from Jarosz et al. (2007): C_d was held constant at 0.0012 for wind speeds less than 11 m/s, increased linearly to 0.0028 up to wind speed of 30 m/s and decreased linearly to 0.0018 for wind speeds larger than 40 m/s.

Fig. 4 shows the water levels associated with the storm. We see that there is a significant increase in water level along the northwestern coast 24 hrs prior to landfall. This phenomenon called the forerunner surge was studied by Kennedy et al. (2011) and shown to be the result of the Ekman setup due to the geostrophic balance between the Coriolis force acting on the along-shelf current and the cross-shelf pressure gradient. By landfall, the surge level increases to about 5 m in the immediate area around Galveston Bay, and 12 hrs after landfall, model results indicate surge level in some localized areas to be still very high, even though it has dropped off to less than 1m in most of the areas.

Tidal amplitudes and velocities are specified along the southern and eastern boundaries of the overall domain. The values are obtained from the TPXO7.2 data, which is the global tidal solution, which best-fits the Laplace Tidal Equations and the along track averaged data from TOPEX/Poseidon and Jason [Egbert et al., 1994, Egbert and Erofeeva, 2002]. For the larger domain, tidal forcing due to gravitational effects of the terrestrial systems is also included. For the inner nest, the tidal forcing is obtained from the results of the larger domain, and the tidal potential forces are not included.

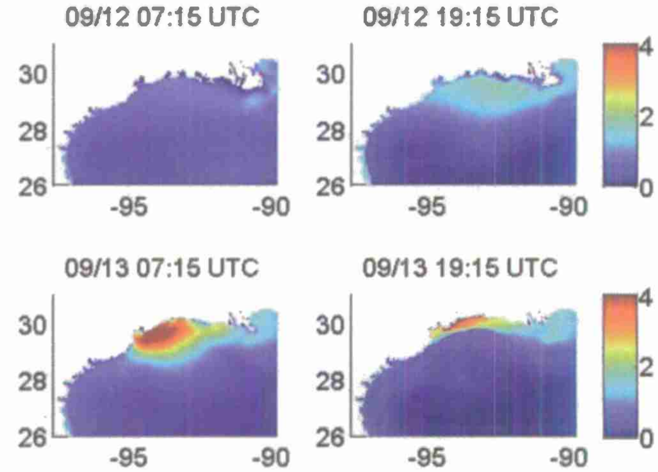

Fig. 4: Water levels (in meters) associated with Hurricane Ike at 24 hrs prior to landfall, 12 hrs prior to landfall, at landfall and 12 hrs after landfall.

The bottom friction also plays an important role in the modeling of storm surge levels. In this setup we use Manning's formulation to model bottom drag with the drag coefficient n=0.02. The surge levels were found very sensitive to this value. Increasing the coefficient to 0.025 completely eliminated the forerunner surge, whereas decreasing the coefficient to 0.015 increased the maximum surge levels by about 1.5 m at locations close to landfall.

As mentioned earlier, the WAVE module was run coupled with the FLOW module. Information was exchanged between the models every hour. To model the transfer of momentum from waves to the mean flow, we use the dissipation method based on Dingemans (1997) rather than the classical radiation stress method of Longuet-Higgins and Stewart (1962). In cases where the model resolution is coarse, the radiation stress method is unreliable due to numerical errors. The dissipation method is more reliable because it uses local quantities rather than spatial gradients and is also more consistent within the momentum budget framework of the model.

The difference in computed water levels with and without the influence of waves is shown in Fig. 5. On the eastern side of the storm (the top four subplots), the inclusion of waves lead to prediction of increased mean water level. With the waves included, the modeled water levels are closer to the observed values over most of the domain. On the west side of the storm, coupling FLOW and WAVE modules results in only a small increase in water levels. The forerunner surge is underestimated in either scenario, but more so without the waves included in the model.

The computed wave heights for four different times are shown in Fig. 6. The time series of the water levels at six buoys in the northern part of the gulf is shown in Fig. 7. The maximum significant wave height 24 hours prior to landfall, when the hurricane was in deeper water, is computed to be a little less than 18 m, which seems very high. The buoy at Southwest Pass, which is at

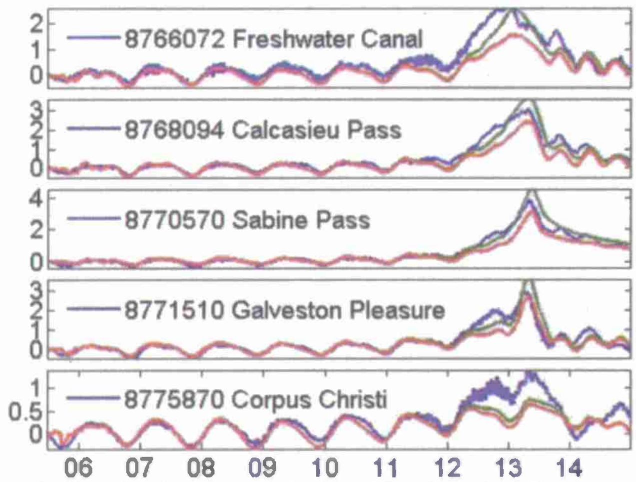

Fig. 5: Water level (in meters) at different locations along the Texas coastline. Blue lines are observed data, red lines are FLOW model results without coupling with WAVE and the green lines FLOW-WAVE coupled results. X-axis shows the days in the month of September.

The computed significant wave heights in the entire domain at selected times are shown in Fig. 6. The time series of the significant wave heights (in meters) for selected locations are presented in Fig. 7. When the storm is outside the continental shelf, the energy is considerably overestimated close to the storm center.

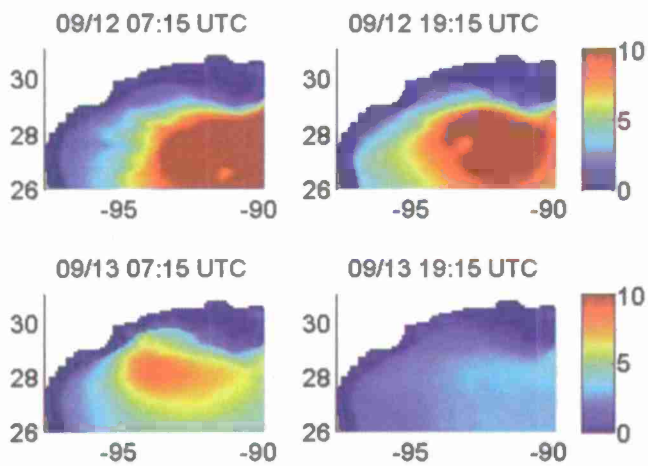

Fig. 6: Significant wave heights (in meters) associated with Hurricane Ike at 24 hrs prior to landfall, 12 hrs prior to landfall, at landfall and 12 hrs after landfall.

The wind effect is modeled in SWAN using the exponential wind growth formulation due Janssen (1991) and the dissipation due to white-capping is modeled based on the pulse-based formulation of Hasselman (1974). Since we expect that the wave field in the vicinity of the storm center would be fully developed, there should exist a balance between the wind input and the dissipation. Both these processes are under investigation as likely reasons for this overestimation of wave energy.

Overall, the model seems to overestimate the wave energy in the domain. In locations closer to the shore, the model seems to estimate the wave energy fairly accurately (see rows 2, 5, 6 in Fig. 7). In shallow water, additional dissipation due to depth-limited breaking is also present. This process is modeled based on the Battjes and Janssen (1978). While the frequency distribution of the wave dissipation is still an ongoing subject of study, the total dissipation in the nearshore due to depth-limited breaking is well modeled by expressions such as those by Battjes and Janssen (1978) and Thornton and Guza (1983). Wave energy along or close to the track of the storm is the one area where the wave energy is consistently overestimated with two notable exceptions that are shown in Fig. 7 – at Galveston where the wave energy is underestimated for a duration of approximately 12 hrs prior to landfall. This issue is likely related to the balance between the white-capping, depth-limited breaking and the wind growth and is part of the aforementioned investigation into the behavior of the wave model.

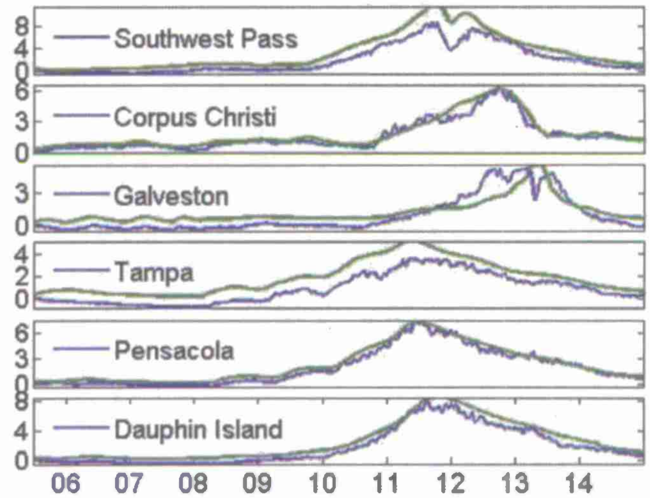

Fig. 7: Significant wave height (in meters) at different locations along the northern Gulf of Mexico. Blue lines are observed data, red lines are model results. X-axis shows the days in the month of September.

CONCLUSIONS

In order to accurately predict storm surge and inundation for purposes of evacuation, post-storm response and humanitarian aid, there is a need to go beyond the current operational methodologies that involve only probabilistic models that use either modeled surge values from historical storms combined with information on historical storm frequencies to estimate local surge hazards or ensemble model runs to determine surge values from a set of parameterized storms. With the oceans getting warmer, past records of hurricane intensity and size may not correspond all the time to the strength of the wind field. Thus deterministic modeling approaches will also have to be undertaken in conjunction with the current approaches to forecast the storm surge. Such models however have to be validated with past storms to ensure their accuracy and reliability. Also, since the deterministic models also make use of certain parameterizations to simplify some of the processes, the accuracy of these parameterizations also has to be checked in relation to modeling the effects of hurricanes. In this study we chose to use the Delft3D modeling suite to model the surge and the wave climate observed during Hurricane Ike, which made landfall in the US as a category 2 storm near Galveston, TX.

Initial results show much promise for the modeling system. The maximum water levels are within 0.5 m of the observed values in most locations. The model was able to predict the forerunner surge that was not expected by the probabilistic models. The effect of waves is found to be important in getting accurate predictions of water level. The grid resolution is important in getting the tidal amplitudes and phases

correct. The wave generation mechanisms during hurricane events need more study and validation. In particular, in the open ocean and near the center of the storm the wave heights are overestimated by more than 50% in some cases. Further investigations focusing on the balance between the wind-growth parameterization and the white-capping mechanism is currently being undertaken to address this problem. Another issue that needs to be addressed is that of the bottom friction. It was found that the surge levels are sensitive to this parameterization. This sensitivity need to be analyzed in detail to determine the error levels in the surge when accurate data is not available regarding the bottom type or the land-use type to model the surge.

REFERENCES

Battjes, JA and Janssen, JPFM (1978). "Energy loss and set-up due to breaking of random waves," *Proc. 16th Int. Conf. Coastal Engineering*, ASCE, pp 569-587

Cox, AT., Greenwood, JA, Cardone, VJ and Swail, VR (1995). "An interactive objective kinematic analysis system," *The Fourth International Workshop on Wave Hindcasting and Forecasting*, Banff, Alberta, Canada.

Dean, RG and Dalrymple, RA (2002). "Coastal processes with engineering applications," Cambridge University Press, 475 pp.

Dietrich, JC , Westerink, JJ, Kennedy, AB, Smith, JM, Jensen, RE, Zijlema, M, Holthuijsen, LH, Dawson, CN, Luettich Jr, RA, Powell, MD, Cardone, VJ, Cox, AT, Stone, GW, Pourtaheri, H, Hope, ME, Tanaka, S, Westerink, LG, Westerink, HJ, and Cobell, Z (2011). "Hurricane Gustav (2008) Waves and Storm Surge: Hindcast, Synoptic Analysis, and Validation in Southern Louisiana," Mon. Wea. Rev., 139(8), pp 2488-2522.

Dingemans, MW, Radder, AC, De Vriend, HJ (1987). "Computation of the driving forces of wave-induced currents," *Coastal Engineering*, Vol. 11, No. 5–6, 539-563, DOI:10.1016/0378-3839(87)90026-3.

Egbert, GD, Bennett, AF, Foreman, MGG (1994). "TOPEX/POSEIDON tides estimated using a global inverse model," *Journal Of Geophysical Research*, Vol. 99, No. C12, 24,821-24,852, doi:10.1029/94JC01894

Egbert, GD, Erofeeva, SY (2002). "Efficient Inverse Modeling of Barotropic Ocean Tides," *J. Atmos. Oceanic Technol.*, 19, pp 183–204. doi: 10.1175/1520-0426(2002)019<0183:EIMOBO>2.0.CO;2

Harris, DL (1963). "Characteristics of the Hurricane Storm Surge," Technical Paper No. 48 (Washington, D.C.: U.S. Dept. of Commerce, Weather Bureau): 139

Hasselmann, K (1974). "On the spectral dissipation of ocean waves due to whitecapping," *Bound-layer Meteor.*, Vol 6, 1-2, pp 107-127

Holthuijsen, LH, Booij, N, Ris, RC, (1993). "A spectral wave model for the coastal zone," *Proceedings of the 2nd International Symposium on Ocean Wave Measurement and Analysis*, New Orleans, pp. 630–641.

Irish, J, Resio, DT, and Ratcliff, J (2008). "The influence of storm size on hurricane surge," *J. Phys. Oceanogr*., Vol 38, 2003-2103.

Irish, J., Resio, DT, and Divoky, D (2011). "Statistical properties of hurricane surge along a coast," *J. Geophys. Res.*, 116, C10007, doi:10.1029/2010JC006626.

Jelesnianski, CP, Chen, J, and Shaffer, WA (1992). "SLOSH: Sea, Lake, and overland surges from hurricanes," NOAA Tech. Rep. NWS 48, 65 pp.

Kennedy, AB. Gravois, U, Zachry, BC, Westerink, JJ, Hope, ME, Dietrich, JV, Powell, MD, Cox, AT, Luettich Jr., RA and Dean, RG (2011). "Origin of the Hurricane Ike forerunner surge," *Geophys. Res. Lett.*, 38, L08608, doi:10.1029/2011GL047090.

Lesser, G R, Roelvink, JA, van Kester, JATM, and Stelling, GS (2004). "Development and validation of a three-dimensional morphological model," *Coastal Engineering*, vol. 51, pp. 883-915.

Longuet-Higgins, MS, Stewart, RW (1964). "Radiation stresses in water waves; a physical discussion, with applications," *Deep Sea Research*, 11 (4), pp 529–562, doi:10.1016/0011-7471(64)90001-4

Powell, MD, Houston, SH, Amat, LR, and Morisseau-Leroy, N (1998). "The HRD real- time hurricane wind analysis system," *J. Wind Eng. Ind. Aerodyn.*, pp 77–78, 53–64, doi:10.1016/S0167-6105(98)00131-7.

Sheng, YP, Alymov, V, and Paramygin, VA (2010). "Simulation of Storm Surge, Wave, Currents, and Inundation in the Outer Banks and Chesapeake Bay during Hurricane Isabel in 2003: The Importance of Waves," *J. Geophys. Res. – Oceans*, 115, C04008, 1–27.

Thornton, EB and Guza, RT (1983). "Transformation of wave height distribution," *J. Geophys. Res.*, 88, C10, pp 5925-5938

REPORT DOCUMENTATION PAGE	*Form Approved* *OMB No. 0704-0188*

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
31-07-2012	Conference Proceeding	

4. TITLE AND SUBTITLE Effect of Coupling Wave and Flow Dynamics on Hurricane Surge and Inundation	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER 0602435N
6. AUTHOR(S) Jayaram Veeramony, Andrew Condon and David Hebert	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER 73-4546-02-5
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Research Laboratory Oceanography Division Stennis Space Center, MS 39529-5004	8. PERFORMING ORGANIZATION REPORT NUMBER NRL/PP/7320--12-1227
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Office of Naval Research One Liberty Center 875 North Randolph Street, Suite 1425 Arlington, VA 22203-1995	10. SPONSOR/MONITOR'S ACRONYM(S) ONR
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release, distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

Inundation that results from tropical storms and hurricanes significantly impact coastal communities. The ability to predict the extent of surge and inundation is essential for evacuation orders, disaster response preparation, and resource planning. In this study we validate the DELFT3D modeling suite comprised of FLOW and WAVE modules to model inundation caused by Hurricane Ike (2008) using reanalyzed data. Model results are compared to the data collected by the SURA coastal inundation testbed. Comparing the effects of coupling waves show that there water levels when coupling waves is substantially greater on the eastern side of the storm where the wind is landward, than on the western side.

15. SUBJECT TERMS

storm surge, unundation, coupled modeling

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Jayaram Veeramony
					19b. TELEPHONE NUMBER *(Include area code)*
Unclassified	Unclassified	Unclassified	UU	5	228-688-4835